RECENT CHANGES IN THE PHYTOPLANKTON OF THE BAY OF QUINTE:

THE RELATIVE IMPORTANCE OF FISH AND PHOSPHORUS

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RECENT CHANGES IN THE PHYTOPLANKTON OF THE BAY OF QUINTE: THE RELATIVE IMPORTANCE OF FISH AND PHOSPHORUS

K.H. Nicholls
Ontario Ministry of the Environment
Water Resources Branch
Aquatic Biology Section
Box 213, Rexdale, Ontario, M9W 5L1

and

D.A. Hurley
Ontario Ministry of Natural Resources
Glenora Fisheries Research Station
R.R.#4, Picton, Ontario, K0K 2T0

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Summary

The effects of eutrophication control in the Bay of Quinte of Lake Ontario, resulting from a 50% reduction in phosphorus loading from municipal wastewater treatment plants in late 1977, have been examined. A major decline in phytoplankton biomass was observed in the highly eutrophic upper bay in 1978. However, in recent years (1982-1985), average May-October phytoplankton biomass increased to levels approaching those of the pre-phosphorus control period, but decreased again during 1986. No major shifts in phytoplankton composition occurred; domination by the diatoms Melosira and Stephanodiscus spp. and the blue-green algae Anabaena and Aphanizomenon spp. has continued. Although N-to-P ratios increased significantly from an average of 11.0:1 during the pre-P control period to 17-20:1 during 1985-1986 in the upper bay, no decrease was found in the proportion of the total phytoplankton contributed by N-fixing blue-green algae.

Phosphorus loading and phosphorus concentrations in the upper bay remained low, relative to the pre-1978 values. No significant correlations existed between total P and total phytoplankton biomass at the upper and middle bay sampling stations, either before or after phosphorus loading reductions; in part, this is because the phytoplankton was often N-limited before 1978. Highly significant positive correlation coefficients ($r = 0.90$-0.96) were found for phytoplankton-planktivorous fish relationships during both pre- and post phosphorus removal periods. A die-off of white perch (Morone americana) in the Bay of Quinte occurred during the winter of 1977-78.

This was followed by several strong walleye (Stizostedion vitreum) year classes, which have apparently since kept white perch numbers low. Between 1981 and 1985, alewife (Alosa pseudoharengus) numbers increased dramatically, but declined again in 1986. It is hypothesized that the combined densities of small sized white perch and alewife have contributed to altered grazing rates on phytoplankton by zooplankton and/or zoobenthos, and have been an important influence on phytoplankton biomass in the upper Bay of Quinte during the period 1972-1986.

SOMMAIRE

On a étudié les effets de la lutte contre l'eutrophisation de la baie de Quinte du lac Ontario, qui a conduit à une réduction de 50 % de la charge en phosphore des stations municipales de traitement des eaux usées à la fin de 1977. On a noté une baisse importante du phytoplancton dans le fond de la baie, très eutrophe, en 1978. Toutefois, au cours des dernières années (1982-1985), la biomasse moyenne en phytoplancton de mai à octobre a atteint des valeurs voisines des valeurs d'avant la période d'élimination du phosphore, mais qui ont de nouveau diminué en 1986. Il ne s'est produit aucune variation importante de la composition du phytoplancton, toujours formé en grande partie de diatomées Melosira et Stephanodiscus spp. et d'algues bleues-vertes Anabaena et Aphanizomenon spp. Le rapport d'azote/phosphore a notablement augmenté, passant d'une moyenne de 11 pendant la période précédant l'élimination du phosphore à 17-20 en 1985-1986 dans le fond de la baie, mais on n'a relevé aucune baisse dans la proportion du phytoplancton total représentée par les algues bleues-vertes qui y fixent l'azote.

La charge et les concentrations en phosphore dans le fond de la baie restent faibles, par rapport aux valeurs d'avant 1978. Il n'existe aucune corrélation notable entre le phosphore total et la biomasse totale de phytoplancton aux postes d'échantillonnage du fond et du milieu de la baie, avant ou après les réductions de la charge de phosphore; cette situation découle partiellement de la limitation fréquente de l'azote dans le phytoplancton avant 1978. On a relevé des coefficients de corrélation positifs très marquants (r=0,90-0,96) pour les rapports phytoplancton-poissons planctivores pendant les périodes antérieures et postérieures à l'élimination du phosphore. Il s'est produit une disparition du baret (Morone americana) dans la baie de Quinte, pendant l'hiver 1977-1978. Elle a été suivie de fortes années de dorés jaunes (Stizostedion vitreum) qui ont apparemment réduit la population de barets. Entre 1981 et 1985, la population de gaspareaux (Alosa pseudoharengus) a considérablement augmenté avant de baisser de nouveau en 1986. On suppose que les densités combinées de barets et de gaspareaux de petite taille ont contribué à modifier l'intensité de la consommation du phytoplancton par le zooplancton et/ou le zoobenthos; on suppose aussi que ces densités ont beaucoup influé sur la biomasse de phytoplancton dans le fond de la baie de Quinte entre 1972 et 1986.

Introduction

The Bay of Quinte of Lake Ontario became highly eutrophied earlier this century and, for a period of several decades, suffered from symptoms of excessive nutrient enrichment including turbid phytoplankton-rich waters, blooms of blue-green algae, bottom water dissolved oxygen depletion, depreciation of the fish and bottom fauna communities and loss of rooted macrophyte vegetation. By the late 1960's, the Bay of Quinte had undergone dramatic changes in the relative composition and biomass of several biotic communities. Most notable were changes in the fish community including loss of large piscivores and increased abundance of smaller planktivorous fish such as alewife (Alosa pseudoharengus) and stunted white perch (Morone americana). The combined effects of exploitation, eutrophication, introduction of non-native species and climatic shifts have generally been cited as the cause of these changes (Hurley and Christie 1977; Hurley 1986a).

"Project Quinte"[1] was initiated in 1972 as a multi-agency, multi-year investigation of the aquatic ecosystem of the Bay of Quinte. It was an attempt to understand some of the important characteristics and processes of a highly eutrophic system before and after major reductions in point-source loadings of phosphorus (Johnson and Hurley 1986).

[1]The findings of Project Quinte spanning the period of scientific investigations from 1972 to the early 1980's were recently published as "Project Quinte: Point-Source Phosphorus Control and Ecosystem Response in the Bay of Quinte, Lake Ontario", C.K. Minns, D.A. Hurley, and K.H. Nicholls [ed.]. Can. Spec. Publ. Fish Aquatic Sci. 86:270p.

Eutrophication of the Bay of Quinte accelerated rapidly during the late 1940's and 1950's with the introduction and subsequent widespread use of phosphate based cleaning compounds (up to 50% by weight as P_2O_5). The expansion of central sewage collection, treatment and disposal systems for growing municipalities in the Bay of Quinte basin was also an important factor. Municipal sewage treatment during this time period generally provided significant reductions in the biological oxygen demand and suspended solids content of the effluents discharged to the Bay of Quinte; however, total phosphorus concentrations in treated effluents were often high, averaging 5-10 mg $P \cdot L^{-1}$. Excessive phosphorus loading to the bay was believed to be the primary cause of high phytoplankton biomass including frequent blue-green algal blooms (Johnson and Owen, 1971; Johnson 1986).

The phytoplankton of the Bay of Quite during the pre-phosphorus control period included over 300 species of algae but was dominated by fewer than a dozen species of diatoms and blue-green algae. Biomass and production rates of this community frequently exceeded 30 $mm^3 \cdot L^{-1}$ and 400 mg $C \cdot m^3 \cdot h^{-1}$, respectively, and are among the highest values known for natural surface waters (Nicholls and Carney 1979; Nicholls et al. 1986; Millard and Johnson 1986). At times, this community was nitrogen limited in the presence of excess phosphorus supply (N-to-P ratios <10:1; Nicholls and Carney 1986). High densities of planktonic algae caused frequent filter clogging and taste and odour problems at treatment facilities utilizing the upper bay as a source of potable water (Nicholls et al. 1986). After the initiation of a phosphorus management programme in late 1977, which resulted in a 50% reduction in phosphorus loading from municipal wastewater treatment

plants, a decrease of about 50% was measured in average May-October phytoplankton biomass. There was, however, continued domination by the same eutrophic species of Anabaena, Aphanizomenon, Melosira and Stephanodiscus. There were marginal shifts in the composition of the phytoplankton which included small increases in the relative proportions of the total contributed by certain chrysophyte and cryptomonad species. These changes, together with the dramatic decline in total phytoplankton biomass and resultant improved water clarity, were interpreted as desirable for food-chain functional purposes (Nicholls et al. 1986).

An evaluation of the early response of phytoplankton to phosphorus loading control (Nicholls et al. 1986) was based on the first four years of the phosphorus control period (1978-1981). There are now available five more years of data which add significantly to our interpretation of the earlier results; in particular, they allow preliminary evaluation of the potential control of phytoplankton via aquatic food-chain interactions in the Bay of Quinte. The purpose of this paper is to present a summary of phytoplankton data collected recently (1982-1986) with special emphasis on analysis of the relative roles of phosphorus and aquatic food-chain interactions as controlling factors.

Methods

The methods of sample collection and analyses of nutrients, phytoplankton, fish and other variables reported in this paper were as outlined by Robinson (1986), Nicholls et al. (1986) and Hurley (1986a). Sampling locations are also unchanged. However, since 1982, fewer

sampling stations have been included in the limnological monitoring and the sampling frequency has been reduced. Bi-weekly sampling now occurs at three sites only (Stations B, HB and C in the upper, middle and lower bay, respectively). Average May-October phytoplankton composition and biomass have been determined on pooled samples (Nicholls et al. 1986). Analyses of all samples collected approximately weekly from the Belleville water supply intake have continued. The term "biomass" has been used to describe phytoplankton density in this paper; measurements have been made as biovolume (mm^3) for Project Quinte sampling stations which was equated to biomass on the assumption that the specific gravity of phytoplankton is = 1.0. Phytoplankton samples collected from the Belleville water treatment plant intake were analyzed independently and quantitatively expressed as Areal Standard Units (A.S.U.) (Nicholls et al. 1986).

Results

During the post-phosphorus control period of 1978-81, the May-October average phytoplankton biomass was reduced to 50% of the pre-phosphorus control period average of 13.1 $mm^3 \cdot L^{-1}$ measured during 1972-1977 in the upper Bay of Quinte (Fig. 1). The yield of phytoplankton per unit total phosphorus during both periods was significantly lower than that predicted from phytoplankton and phosphorus data from other areas of the Great Lakes (Fig. 1). More recently there has been a well defined trend to much higher phytoplankton biomass in the upper bay, both in samples from the Belleville water intake and from

Project Quinte Station B (Fig. 2). The 1985 May-October average of 13.3 $mm^3 \cdot L^{-1}$ at Station B is comparable to values recorded during the pre- phosphorus control period of 1972-1977. These recent increases in the upper bay were also substantiated by elevated chlorophyll a concentrations and vertical light extinction coefficients (E.S. Millard, Dept. Fish. & Oceans, CCIW, Burlington, unpublished data). In contrast, May-October total phosphoru concentrations at Station B changed little between 1978 and 1985 (Figs. 1, 2).

Phytoplankton biomass declined dramatically in 1986 (6.7 $mm^3 \cdot L^{-1}$), as did average total phosphorus concentration in the upper bay (33 µg $P \cdot L^{-1}$). Point-source phosphorus loadings were substantially lower after 1977 and were the lowest on record in 1985 (Table 1).

No dramatic changes have occurred in the phytoplankton composition of the upper bay. Although the Dinophyceae were only a minor component of the upper bay phytoplankton during the earlier years of the study (averaging 4% of the total during 1972-1977), this group has declined in importance in recent years to a level similar to that contributed by the Chrysophyceae (about 1% of the total phytoplankton; Table 2).

Bacillariophyceae (diatoms) and Cyanophyceae (blue-green algae) have continued to dominate the May-October periods. Total diatom biomass has been about 2-4 X greater than blue-green algal biomass, but the combined totals of these two groups have consistently provided more than 85% of the total phytoplankton biomass (Table 2). The diatoms Melosira granulata (Ehr.) Ralfs and M. ambigua (Grun.) O. Müll have continued to dominate. The average 1985 Melosira biomass (9.5 $mm^3 \cdot L^{-1}$) was higher than values recorded for the May- October periods of all

previous years (Fig. 3). Although much less dominant over the years, Stephanodiscus spp., mainly S. astraea (Ehr.) Grun. (see taxonomic footnote in Nicholls et al. 1986, p.147), S. hantzschii Grun. and S. invisitatus Hohn & Hellerman, have not increased. The average biomass of Stephanodiscus spp. during 1978-1985 (0.33 $mm^3 \cdot L^{-1}$) was significantly less ($P < 0.05$) than the average (1.14 $mm^3 \cdot L^{-1}$) recorded for the pre- phosphorus control period of 1972-1977 (Fig. 3).

The highest silicate levels were found in 1978 and 1979 immediately following phosphorus loading reductions; however, average silicate concentrations have declined again in recent years with the increased prevalance of Melosira (Fig. 3).

Over the entire 15 year period of observation, the nitrogen-fixing blue-green algae Anabaena and Aphanizomenon have been the most important elements of the cyanophycean flora, comprising between 54% (1975) and 75% (1981) of the total blue-green algal biomass. The lowest combined biomass of these two genera was found during 1978, the first year after significant point-source phosphorus loading reductions; the highest was found in 1984 (Fig. 4). Total N-to-total P ratios have increased significantly over the 1972-1986 period (Fig. 4; $r = 0.882$); however, the contribution of N-fixing blue-green algae (Anabaena and Aphanizomenon spp.) to the total phytoplankton has not changed significantly ($P > 0.05$), averaging 13.5% and 20% of the total phytoplankton biomass for the pre- (1972-1977) and post (1978-1986) phosphorus control periods, respectively.

While total phytoplankton and total phosphorus concentrations in the Bay of Quinte for the 1972-1981 period were highly correlated when average data from all sampling stations were included (Nicholls et al. 1986), similar correlations are not evident when data analyses are restricted to single stations and separated into pre-and post P removal time periods. Correlation coefficients of only 0.073 and 0.006 were determined for phytoplankton-total phosphorus relationships at Station B for the 1972-1978 and 1980-1986 periods, respectively (Fig. 5a, 6a). Johnson (1986) has shown significant correlations between four algal related measures of response and point-source P load and % point-source P load. However most of the data points were grouped into two grouped into two separate clusters for the pre-and post removal periods (see Johnson's Fig. 2). No significant correlations ($\underline{P}>0.05$) were found for the smaller data sets representing the separate pre-and post P removal periods.

In contrast, highly significant correlation coefficients ($\underline{P}<0.01$) were found for phytoplankton-planktivore relationships for the same two time periods ($r = 0.908$ and $r = 0.959$; Figs 5b and 6b). Similar relationships were found for the phosphorus- phytoplankton-planktivore data from Station HB in the middle bay for the 1972-1978 period (Fig. 7). For some of the phytoplankton <u>vs</u> fish relationships, the correlation coefficients were improved if rainbow smelt (<u>Osmerus mordax</u>) was included, either in place of alewife or in addition to alewife and white perch (Fig. 8).

Discussion

The relationships of the algal related variables with elements of the Bay of Quinte food-chain are poorly understood; ".....linkages between primary producer dynamics and secondary production, especially fish, continue to be elusive....." (Johnson 1986). Similarly, Hurley et al. (1986) concluded that "phosphorus reduction produced the initial reaction in phytoplankton biomass ... and ... predator-prey interactions have been effective (only) at the higher trophic levels". Now that five additional years of data are available (1982-1986), these relationships can be more critically examined. The important question now seems to be, to what extent were phosphorus loading controls responsible for the initial phytoplankton decline in 1978, and how important were food-chain effects, during both the pre- and post phosphorus control periods?

In contrast to the nitrogen limited state which prevailed in the upper Bay of Quinte during the pre-phosphorus control period, N-to-P ratios averaging 13.3-18.9 suggest that phytoplankton in the upper bay has been primarily phosphorus limited rather than N limited during the post phosphorus removal period (Nicholls and Carney 1986; Millard 1986). As would be expected under conditions of N limitation, a significant correlation between phytoplankton and total P was not found ($r = 0.073$, Station B, 1972-1978). The relationship between phytoplankton and total N was better defined, but, probably because N alone was not always limiting, the correlation coefficient ($r = 0.539$) was not statistically significant ($P > 0.05$).

Assuming a critical total N-to-total P ratio of 10 as the threshold for N limitation (Nicholls and Carney 1986), total N concentrations can be expressed as "critical phosphorus equivalents" and the combined effects of N and P were evaluated by linear regression analysis. The correlation was measurably improved over those found for the separate phytoplankton-phosphorus and phytoplankton-nitrogen relationships:

$$\underset{\substack{(mm^3 \cdot L^{-1}) \\ \text{(upper Bay of Quinte,} \\ \text{1972-1978)}}}{\text{phytoplankton}} = 0.13 \underset{(\mu g \cdot L^{-1})}{\left[\frac{N}{10} + P\right]} - 7.7 \quad (r = 0.719)$$

Only about 50% of the variance ($r^2 = 0.517$) in upper bay phytoplankton biomass is accounted for by the above relationship with nitrogen and phosphorus. The highly significant relationship between phytoplankton and zooplanktivorous fish ($r^2 = 0.824$; $\underline{P} < 0.01$) offers a reasonable explanation for the residual variance in phytoplankton biomass. Given the three correlation coefficients $r_{12} = 0.719$, $r_{13} = 0.908$ and $r_{23} = 0.736$, where:

1 = phytoplankton biomass, Station B

2 = nitrogen and phosphorus as "phosphorus equivalents" $\left[\frac{N}{10} + P\right]$

3 = alewife + white perch, upper bay trawl CUE,

a highly significant multiple correlation coefficient was found for phytoplankton biomass $\underline{vs}\left[\frac{N}{10} + P\right]$ and alewife + white perch for the 1972-1978 period:

$$r_{1 \cdot 23} = 0.911 \ (\underline{P} < 0.005)$$

It is sometimes dangerous to assume direct cause and effect from statistical correlations; however, in this case, both of the relationships between phytoplankton and fish and phytoplankton and phosphorus can be defended by ecological theory and experience. It may be possible therefore to determine the relative measures of importance of nutrients and fish as factors determining phytoplankton biomass in the Bay of Quinte, based on partial correlation analysis (i.e. the relationship between two variables after the effects of the third variable have been removed).

There was no significant correlation between phytoplankton and the combination of N and P ($r = 0.180$) when the influence of the fish-phytoplankton relationship was removed. In contrast, the partial correlation coefficient for the relationship between phytoplankton and fish was $r = 0.805$, after the influence of the phytoplankton-N + P relationship was removed. The reasons for the observed decline in phytoplankton biomass after the 1977 phosphorus loading reductions can therefore be apportioned approximately as follows: 80% to fish (food-chain) effects and 20% to phosphorus concentration reductions. Clearly, nutrients have had an even less important role in the recent

increase in phytoplankton biomass since 1978 because phosphorus concentrations have been essentially unchanged (excluding 1986). The real rate of increase of average total P concentration based on the slope of the regression line for 1978-1985 was <0.7 $\mu g\ P \cdot L^{-1} \cdot yr^{-1}$.

The well-defined phytoplankton-fish relationships for the separate periods of 1972-1978 and 1980-1986 were not continuous over the entire 1972-1986 period. There was an apparent 1-2 year period of adjustment after 1977 when the trophic interactions in the Bay of Quinte undoubtedly changed as a result of the combined effects of the 1977 white perch die-off (ascribed to climatic factors, Hurley, 1986a) and the decreased phosphorus loading.

There is mounting evidence that trophic level interactions in aquatic systems help determine production and biomass of the algal component of the food chain (Shapiro 1980; Shapiro and Wright 1984). For purposes of illustration, a 3-step (4-component) trophic system is assumed to dominate in the Bay of Quinte (Fig. 9) which includes walleye among the large piscivores, alewife and small sized white perch as the dominant planktivores, several cladoceran and calanoid copepod species as filter feeding zooplankton and the phytoplankton dominated by large celled or colonial diatoms and blue-green algae. In theory, increases in phytoplankton biomass can be achieved by either increasing the nutrient supply or by decreasing the abundance of large piscivores (scenarios 2 and 4 of Fig. 9). The impact of nutrient loading changes beyond the primary producer level is greatly dampened by high loss rates through sedimentation and other factors and may not lead to altered production rates and biomass at higher trophic levels (hence

the small arrows linking these components in Fig. 9), especially if food supply is not limiting at each of these levels. McQueen et al (1986) have suggested that the control of biomass at each trophic level, by changes in nutrient supply, weakens by a factor of 2 with each succeeding step up the food web. They also suggest that "top-down effects" (i.e. the effects of changes in biomass of piscivores on lower trophic levels) will be more buffered in eutrophic lakes than in oligotrophic lakes.

In the Bay of Quinte food-chain, relationships between trophic components should be best defined for adjacent components and be less well defined for functionally remote components. For example, the expected negative correlation between phytoplankton and zooplankton should be better defined than the expected negative correlation between phytoplankton and large piscivores. This is because trophic interactions alone are not the only determinants of abundance levels in each component. While the abundance of large piscivores will help determine abundance of smaller planktivorus fish, other factors such as availability of suitable habitat and environmental factors governing success of spawning and cohort recruitment are also important. In the Bay of Quinte, the most dramatic example of this was the 1977 crash of the white perch population which was apparently related to a winter kill and not to any major increase in predation pressure (Hurley 1986a). For reasons such as these, relationships between phytoplankton biomass and piscivore biomass are not expected to be as well defined as the phytoplankton-planktivore relationships. Probably for similar reasons, the relationship between walleye and alewife + white perch has not been

particularly well defined although it was statistically significant for the Hay Bay trawl data, 1972-86 (no data for 1982):

Alewife + white perch = -47.7 x walleye CUE + 772

(CUE, Hay Bay trawl) ($r = -0.573$; $P < 0.05$)

The same arguments can be used to suggest that the expected negative correlation between phytoplankton and zooplankton biomass should be stronger than the positive correlation between phytoplankton and zooplanktivorous fish. Zooplankton data are not available for all years of the Project Quinte investigation (Cooley et al. 1986); however, the recent data for the upper bay (J. Cooley, Dept. Fish. and Oceans, CCIW, Burlington, unpublished data) show average biomass of total cladocera during 1982- 1985 was nearly 2 X higher than for the period 1975-76 and 1979-81. Hence, for 1979-81 vs. 1982-85, these data do not fit the predation-grazing theory suggested by the planktivore-phytoplankton relationships (however, they do fit for 1975-76 vs. 1982-85). Reasons for this apparent anomaly are not immediately clear. Total cladoceran biomass in the upper bay has been dominated by small bodied forms, especially Chydorus sphaericus (Cooley et al 1986), which have not been important food items for planktivores (Hurley 1986b). Also, C. sphaericus is unlikely to utilize large algae like Melosira spp. which dominate the Bay of Quinte. Data are needed on the biomass of large filter-feeding calanoids and cladocera which are of much more potential significance as algal grazers and as food items for planktivorous fish than the smaller Chydorus sphaericus, Bosmina and Eubosmina

spp. (Carpenter et al 1985). Hurley (1986b) concluded that the large calanoids Limnocalanus macrurus and Diaptomus sicilis were being actively selected by alewife while the small cladocerans were not. Similarly, in the upper bay, white perch were actively selecting Daphnia pulex, Latona setifera and Ilyocryptus spinifa over the much more abundant smaller cladocerans (Hurley 1986b).

Hurley et al. (1986) noted a trend to greater biomass of larger zooplankton after 1977 and that these biomasses were negatively correlated with numbers of small fish taken in index trawls; for the upper-middle bay the regression was:

$$\log_{10} \text{macrozooplankton biomass } (mg.L^{-1}) = -0.705 - [0.568 \log_{10} \text{alewife biomass } (mg \cdot L^{-1})]$$

where macrozooplankton were defined to include all zooplankton animals 10 µg (dry weight) and greater ($P<0.005$). These relationships apparently do not extend to the phytoplankton in the form of statistically significant negative correlations between phytoplankton and macrozooplankton. A lack of correlation between phytoplankton and macrozooplankton may mean that some other species also utilized as food by forage fish exerts a greater grazing effect on phytoplankton than the macrozooplankton. In the relatively shallow upper bay, herbivorous benthic invertebrates (e.g. ostracods?) may be important, but no information on annual populations exists. Johannsson and Beaver (1983) showed that Melosira was an important food item for benthic midge larvae in the Bay of Quinte.

The importance of the point-sources of phosphorus loading relative to the diffuse inputs has been demonstrated for the Bay of Quinte. Significant correlations were found between independent trophic state variables and point-source loading, but not with total phosphorus load (Johnson 1986). The return to much higher phytoplankton biomass in recent years has occurred despite continued success with the phosphorus control programme at municipal wastewater treatment plants discharging to the Bay of Quinte. During 1985, point-source loadings of total phosphorus were the lowest on record. Phosphorus concentrations averaging less than 50 μg $P \cdot L^{-1}$ (in contrast to 70-90 μg $P \cdot L^{-1}$ during 1972-77) during the May-October periods of 1978-1985 were consistent with these reduced loadings. Point-source loading was higher in 1986 than in 1985 (G. Owen, Ont. Ministry of the Environment, Kingston, unpublished data) but because of unusually high flows from the Trent River (B. Kitchen, Environment canada, Peterborough) the resultant high dilution contributed to the lowest average total phosphorus concentration yet observed in the upper bay (33 μg $P \cdot L^{-1}$).

Planktonic algae respond to phosphorus concentrations created by the combined effects of phosphorus and water loading. Phosphorus concentration sets the upper limits on phytoplankton biomass, while other factors such as zooplankton grazing and displacement or dilution effects on algal cells determine the extent to which these upper limits are realized. Measurements of phosphous concentration in the Bay of Quinte, therefore, integrate the measures of P load and water load; however the direct effects of flow on phytoplankton are not readily quantified. An attempt was made through multiple linear regression

analysis to determine the relative significance of flow on average phytoplankton biomass. Recent flow data were not available for all rivers, so data from only the Trent River (Glen Ross gauging station) were used. The Trent River drains 80% of the land area above Station B in the upper bay and is therefore a useful index of total water input to the upper bay.

May-October average phytoplankton biomass was inversely related to Trent River flow ($r = -0.585$), but was not statistically significant ($P > 0.05$). The incorporation of flow into the phytoplankton-zooplanktivorous fish relationship as a second independent variable did not improve the predictability of average phytoplankton biomass:

$$\underset{(mm^3 \cdot L^{-1})}{\bar{X}\ \text{phytoplankton}} = 5.19 - \frac{11.16}{f} + 0.003\ (\text{alewife} + \text{white perch}) \times \text{C.U.E. gillnet}$$

where f = May-October Trent River flow (1980-1986).

The multiple correlation coefficient is $R = 0.921$. A slightly higher multiple correlation coefficient of $R = 0.939$ was determined for phytoplankton *vs* $[P]$, $\frac{1}{f}$ and alewife + white perch. However, the best predictior of average phytoplankton biomass appears to be alewife + white perch C.U.E. alone (Fig. 6).

There may be some danger in assessing the long-term May-October average effects of grazing rate, P load and flushing rate on phytoplankton biomass because each of these controlling factors may be dominant influences for only short time periods during the growing season. However, the evidence suggests that average abundance of certain fish stocks in the Bay of Quinte may be a very important factor for the indirect control of average May-October phytoplankton biomass. This is supported by recent studies elsewhere in the Great Lakes. In Lake Michigan, changes in alewife populations and densities of zooplankton and phytoplankton (Edgington, 1985; Scavia et al 1986; Evans, 1986) suggest that trophic interactions may be a very significant feature of large lakes.

It is apparent that the implications of the recent Project Quinte findings are potentially very important. It is possible that in many situations, control of eutrophication problems (e.g. blooms of potentially toxic blue-green algae, bad taste and odour in drinking water supplies, depreciation of high quality recreational swimming opportunities, etc.,) cannot be achieved by reduced nutrient loading alone but, rather, must depend on the combined effects of nutrient loading control and management of fish habitat and fish community structure.

In the Bay of Quinte, re-establishment of a stable fish community dominated by desirable predator species (the larger piscivorous percids, centrarchids and esocids) may also depend on the re-establishment of extensive macrophyte beds in the Bay of Quinte. These plant communities were lost from large areas of the upper bay 20-30 years

ago, presumably as a consequence of proliferation of phytoplankton and a resultant "shade-out" effect. Experimental procedures designed to accelerate the recolonization of macrophytes should be a major thrust of the agencies participating in Project Quinte in the future. It is also apparent that the role of food chain interactions in controlling some symptoms of eutrophication needs to be better understood so that the greatest potential benefits of reduced phosphorus loading can be achieved by simultaneous management of other components of the Bay of Quinte ecosystem.

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Table 1: Inputs of total phosphorus from wastewater treatment plants discharging to the upper Bay of Quinte (Trenton, CFB-Trenton, Belleville). Estimates are made for the entire year (annual) and for the May-October period only.

	Kg P· day⁻¹	
	annual	May-October
1965-72	176	NA[b]
1972-75	126	NA
1976	90	NA
1977	77	NA
1978	42	40
1979	32	22
1980	39	29
1981	47	44
1982	44	39
1983	43	26
1984	52	45
1985	29	20

a Data supplied by G. Owen, Ont. Ministry of the Environment for the 1985 Project Quinte Annual Report.

b Estimate not available.

Table 2: Summary of May-October average phytoplankton as a percentage of total biovolume (dominant algal classes) at Station B in the upper Bay of Quinte, 1972-1986.

	Percentage of Total					
	Cyano-phyceae	Dino-phyceae	Crypto-phyceae	Chryso-phyceae	Chloro-phyceae	Bacillario-phyceae
1972	17	3	3	<1	4	73
1973	20	6	4	1	3	66
1974	11	4	2	<1	2	82
1975	16	5	3	1	7	68
1976	22	1	3	1	4	70
1977	20	4	4	<1	6	65
1978	17	4	4	2	6	67
1979	27	4	3	<1	3	62
1980	21	2	6	2	4	65
1981	34	1	3	1	4	51
1982	13	1	2	<1	2	81
1983	21	<1	2	2	4	70
1984	39	1	3	1	2	54
1985	17	1	2	1	2	77
1986	27	<1	4	1	4	63

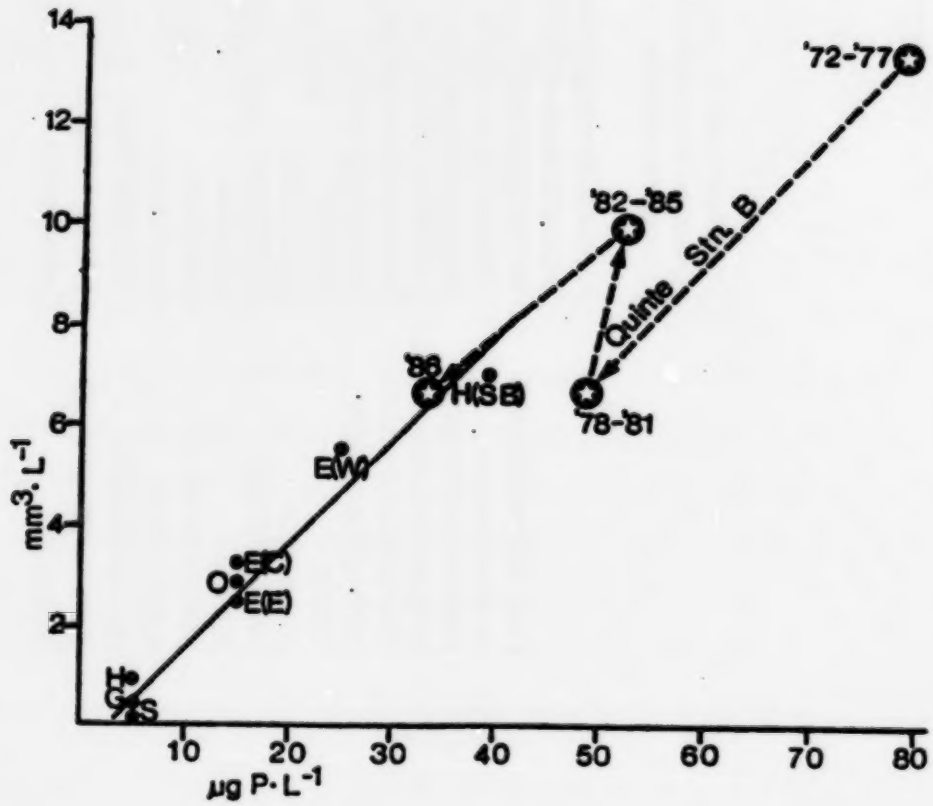

Fig. 1. Changes in May-October phytoplankton biomass ($mm^3 \cdot L^{-1}$) and total phosphorus concentrations ($\mu g\ P \cdot L^{-}$) at Station B in the upper Bay of Quinte 1972-1986. Also shown are average values for other Great Lakes locations, keyed as follows: H(SB) - Saginaw Bay of Lake Huron; E(W), E(C) and E(E) - Lake Erie, western, central and eastern basins, respectively; O - Lake Ontario; H - Lake Huron; G - Georgian Bay; S - Lake Superior. Data sources include Bierman and Dolan (1981), Munawar and Munawar (1981) and Weiler (1981).

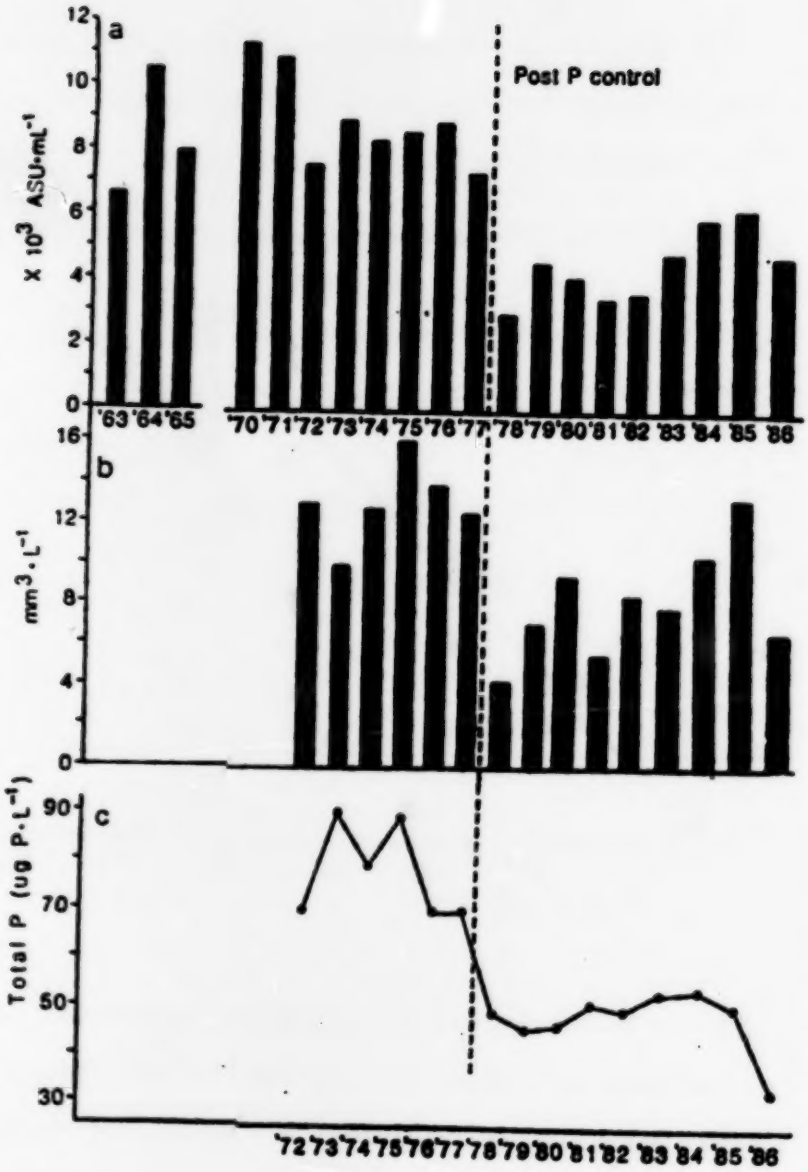

Fig. 2. Average May-October densities of total phytoplankton in samples collected (a) through the Belleville water treatment plant intake and (b) at Station B in the upper Bay of Quinte. Also shown (c) are average total phosphorus concentrations over the same time period at Station B.

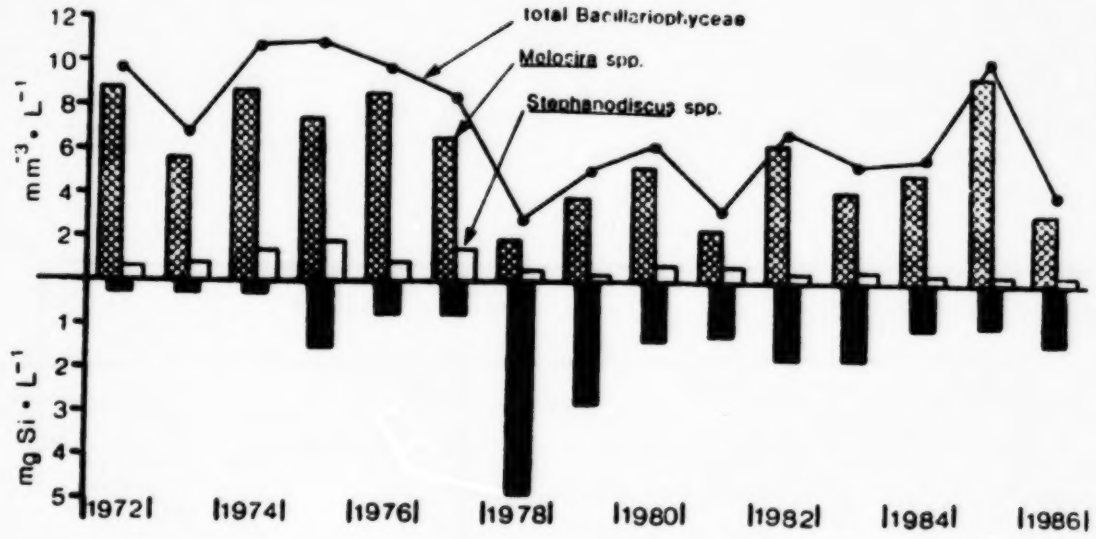

Fig. 3. Total Bacillariophyceae (diatom) biomass and the two major generic components, Melosira and Stephanodiscus over the May-October periods of 1972-1986 at Station B in the upper Bay of Quinte. Also shown are dissolved silicate levels (mg Si·L^{-1}) over the same time at Station B.

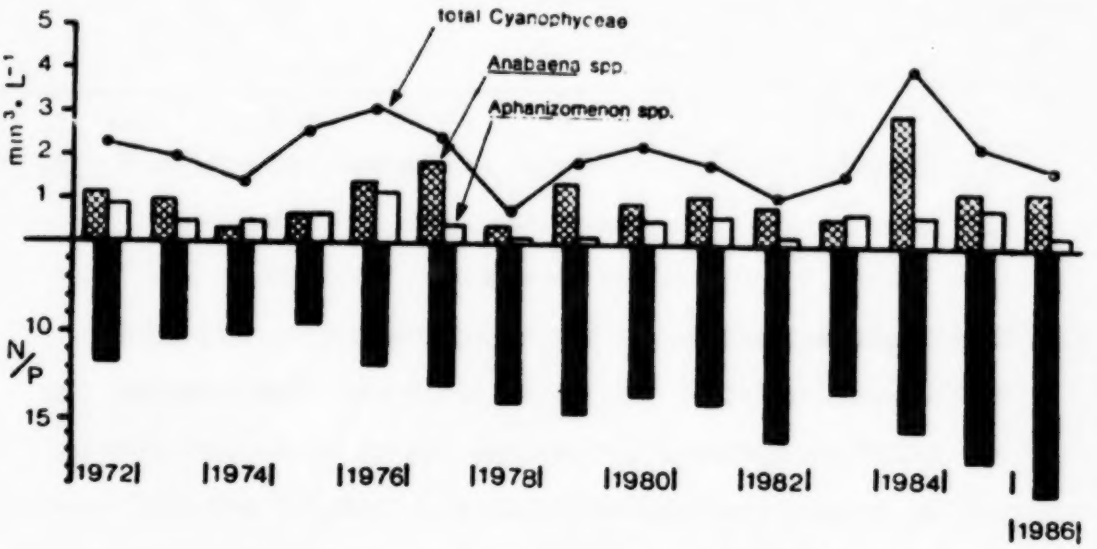

Fig. 4. Total Cyanophyceae (blue-green algae) biomass and the two major generic components, Anabaena and Aphanizomenon over the May-October periods of 1972-1986 at Station B in the upper Bay of Quinte. Also shown are total N-to-total P ratios over the same time at Station B.

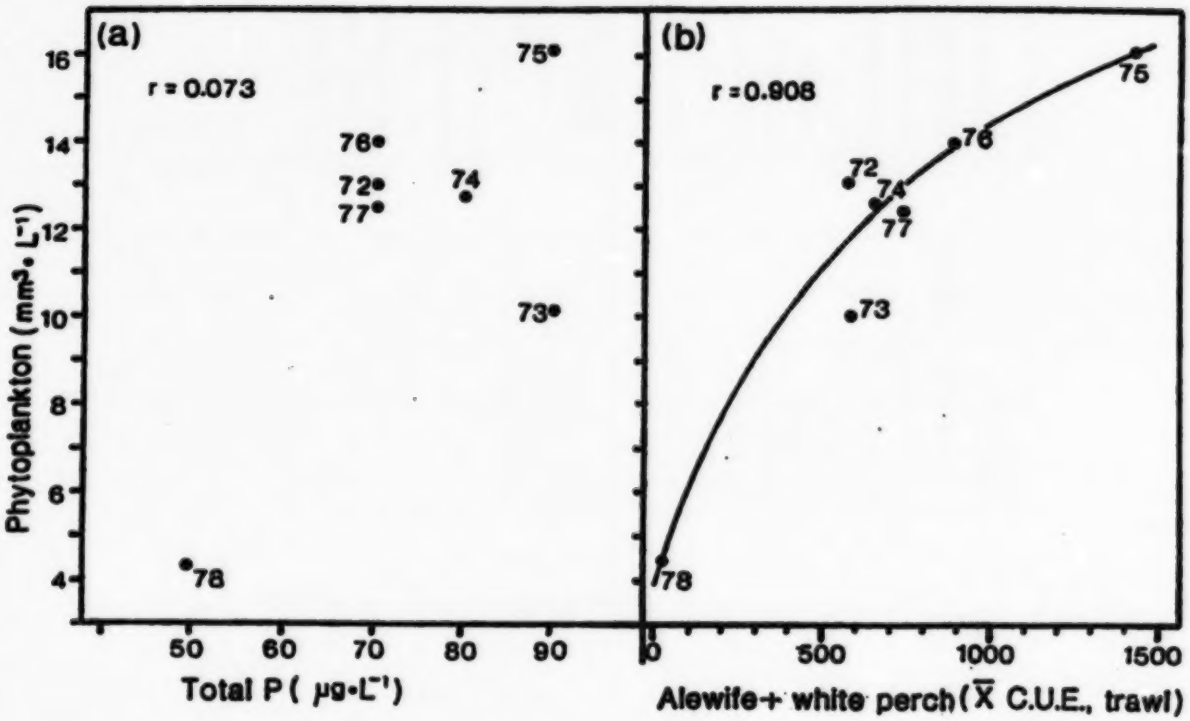

Fig. 5. Relationships between (a) May-October average phytoplankton biomass ($mm^3 \cdot L^{-1}$) and total phosphorus concentration ($\mu g\ P \cdot L^{-1}$) at Station B in the upper Bay of Quinte 1972-1978 and (b) average phytoplankton biomass at Station B and mean catch per unit effort (C.U.E.) of the dominant planktivores (alewife and white perch) for standard bottom trawl drags in the upper Bay of Quinte.

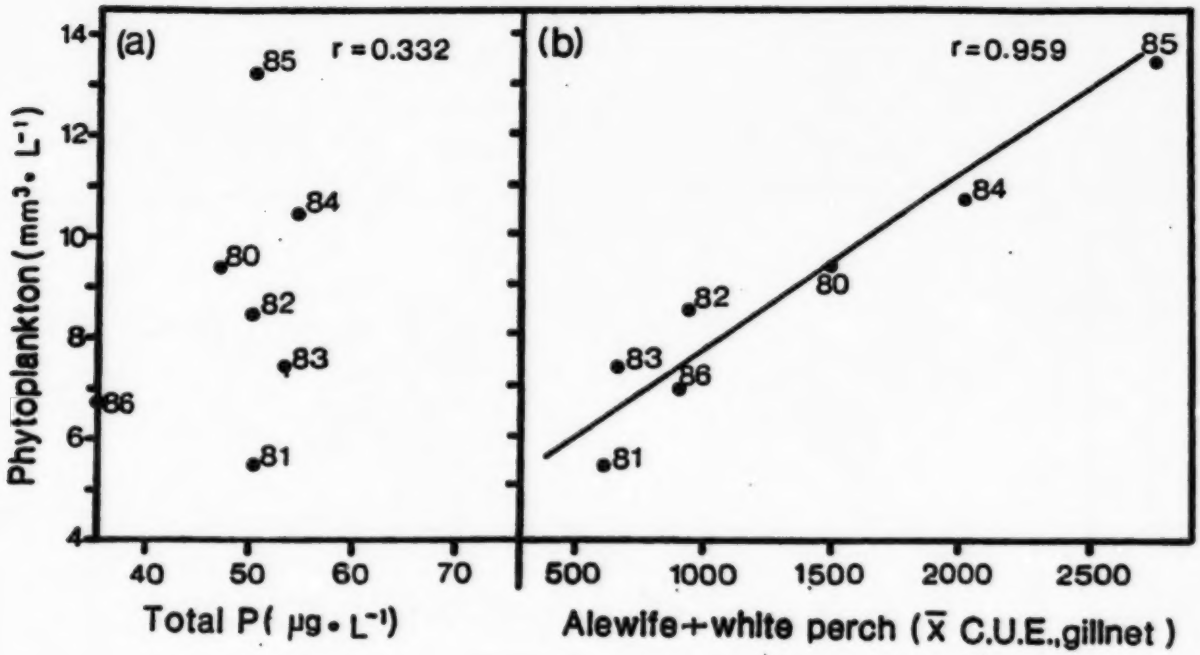

Fig. 6. Relationships between (a) May-October average phytoplankton biomass ($mm^3 \cdot L^{-1}$) and total phosphorus concentration ($\mu g\ P \cdot L^{-1}$) at Station B in the upper Bay of Quinte 1980-1986 and (b) average phytoplankton biomass at Station B and mean catch per unit effort (C.U.E.) of the dominant planktivores (alewife and white perch) for standard experimental gill net lifts from the Bay of Quinte. Trawling was not done in 1982 and gill nets were not set in the upper bay in 1985, so data from the middle Bay of Quinte gill net sets were used here.

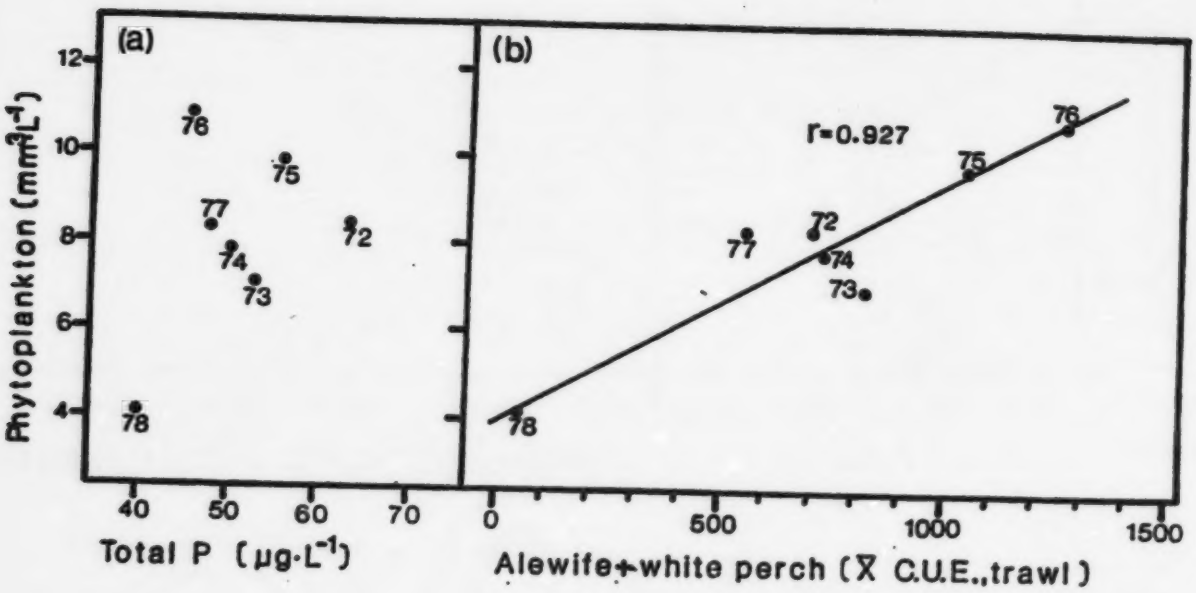

Fig. 7. Relationships between (a) May-October average phytoplankton biomass ($mm^3 \cdot L^{-1}$) and total phosphorus concentration (µg $P \cdot L^{-1}$) at Station HB in the middle Bay of Quinte 1972-1978 and (b) average phytoplankton biomass at Station HB and mean catch per unit effort (C.U.E.) of the dominant planktivores (alewife and white perch) for standard bottom trawl drags in the upper and middle Bay of Quinte.

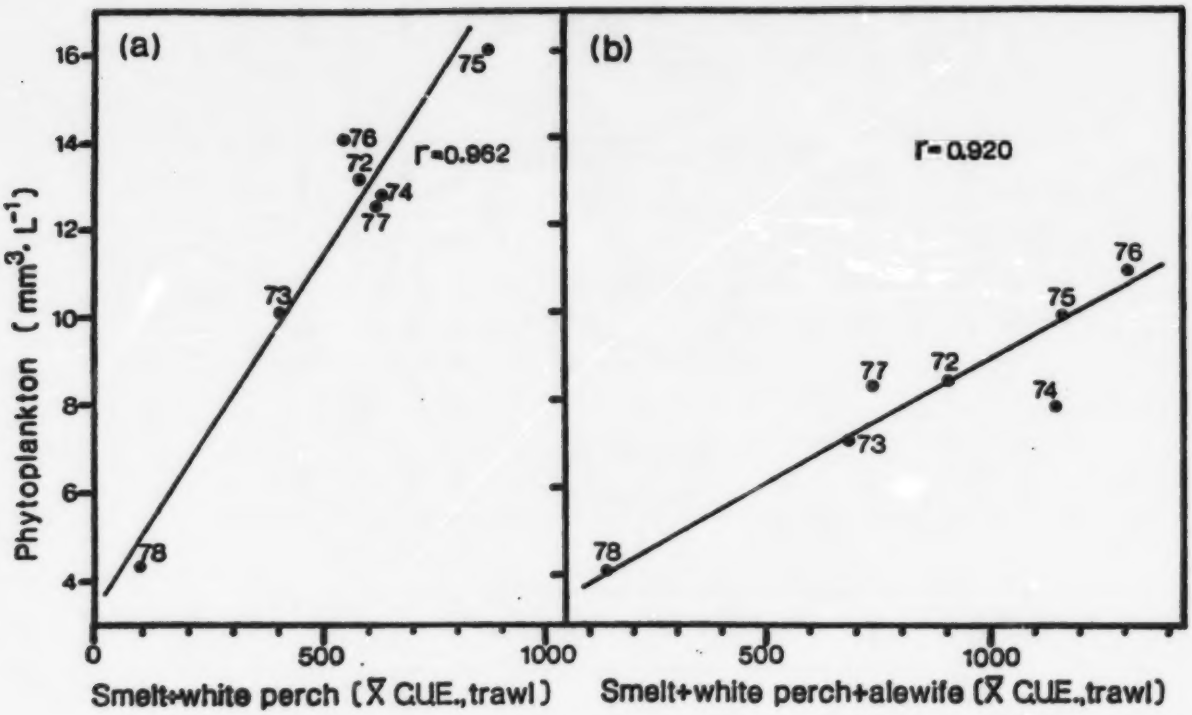

Fig. 8. Relationships between (a) May-October average phytoplankton biomass ($mm^3 \cdot L^{-1}$) at Station B in the upper Bay of Quinte and mean catch per unit effort (C.U.E.) for smelt + white perch in standard bottom trawl drags in the upper and middle Bay of Quinte and (b) phytoplankton biomass at Station HB in the middle Bay of Quinte and mean C.U.E. for smelt + white perch + alewife in standard bottom trawl drags in the upper and middle Bay of Quinte.

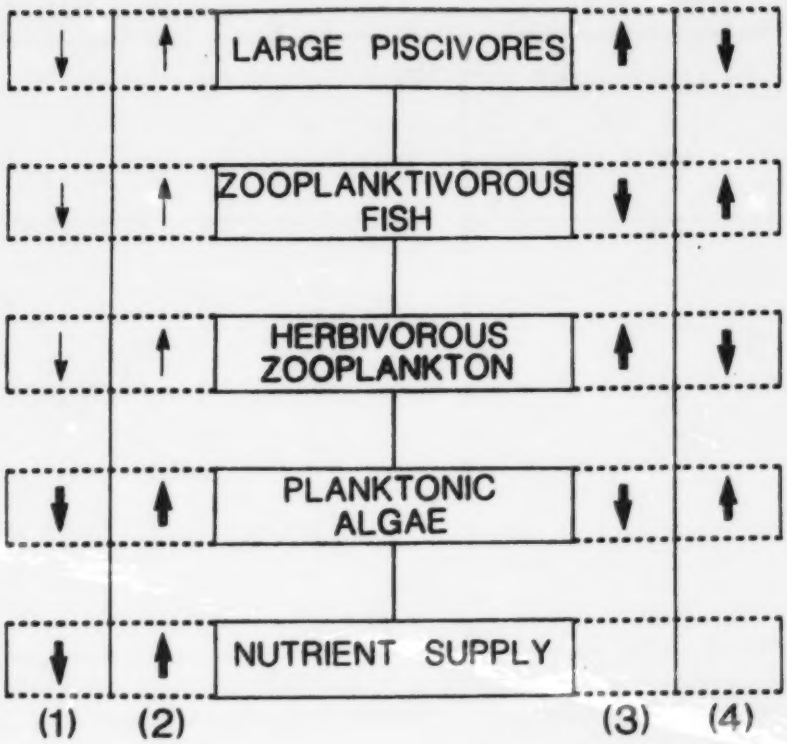

Fig. 9. Preliminary hypothesis of the major trophic compartments in the upper Bay of Quinte. Scenarios 1 and 2 alter the rate of nutrient supply and scenarios 3 and 4 hold nutrient supply constant but alter the abundance of large piscivores. In the Bay of Quinte, the benthic community (insect larvae, ostracods, etc.,) may be a more important functional link between forage fish and phytoplankton than herbivorous zooplankton.